Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Michael Apted

Technical Note

2014:43

Workshop on general corrosion of copper

Main Review Phase

Report number: 2014:43 ISSN: 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information och göra expertbedömningar i avgränsade frågor. Workshopar organiseras sedan för att diskutera läget för SSM:s aktuella granskningsinsatser samt konsulternas uppdragsresultat om specifika processer, säkerhetsfunktioner och barriärer av stor vikt för SKB:s säkerhetsanalys SR-Site för kärnbränsleförvaret i Forsmark. Synpunkter samt slutsatser som resulterar från workshoparna är workshopdeltagarnas syn och inte nödvändigtvist SSM:s.

Workshopens syfte

Det övergripande syftet med workshoppen har varit att identifiera och utvärdera viktiga faktorer som påverkar allmän korrosion av kopparkapslarna som används i KBS-3 metoden för slutförvar av radioaktivt bränsle, och som på sikt skulle kunna generera skador. SSM och externa experter inom områdena grundvattenflöde, geokemi, buffert- och materialbeteende samt säkerhetsbedömning deltog i workshopen.

Sammanfattning av workshopen

Rapporten beskriver resultatet från en workshop som SSM organiserade om allmän korrosion av kopparkapseln den 26-27 augusti 2013. Rapporten redovisar de frågeställningar som diskuterats samt summerar viktiga synpunkter som uppnåtts. Redovisningen bör inte ses som en fullständig dokumentation av alla diskussioner under workshopen och individuella påståenden från deltagarna bör hanteras som deras uppfattning och inte SSM:s ståndpunkter.

Informationen, argumenten och analyserna som presenterades i workshopen visar att inga säkerhets- signifikanta konsekvenser för den allmänna korrosionshastigheten av kopparkapslarna eller antalet kapslar som kan skadas genom korrosion för antingen fallet med intakt buffert eller med eroderad buffert har identifierats. Anledningen till låg känslighet för eventuell erosion av buffert beror på flera faktorer, främst från den antagna tillämpningen av kriterier för val av deponeringshål (d.v.s. att utesluta hål med höga grundvatteninflöden från olika sprickor).

Låg erosionshastighet skulle kunna vara en annan förmildrande faktor när det gäller säkerhets- betydelse av eventuella konsekvenser för fallet med eroderad buffert, särskilt när extrema spekulativa degraderingsmodeller eller kombinationer av degraderingsmodeller beaktas. Dessa erosionshastigheter förväntas bli låga för redovisade fördelningar av flöden och sprickgeometri i Forsmark. Därför kan signifikant bufferterosion som skulle tillåta advektiva flödesförhållanden endast kunna förekomma i några deponeringshål under en framtida glaciation, i en tid då radioaktivi-

teten i det använda kärnbränslet har minskat betydligt.
Några farhågor togs upp vid workshopen gällande processer eller alternativa modeller / antaganden som skulle kunna ändra SKB: s säkerhetsanalyser.

1. Sänkning av buffertdensitet i en eroderad buffert skulle kunna möjliggöra inträde av mikrobiell aktivitet före uppkomsten av advektiva flödesförhållanden. Det är möjligt att mikrobiell reduktion av löst sulfat (vid mycket högre koncentrationer än för lösta bisulfider) vid kapselytan skulle kunna höja allmänkorrosionshastigheten för kapslar vid förhållanden med delvis eroderad buffert (om än för samma begränsade antal deponeringshål som anses av SKB).
2. Kan tillämpningen av en alternativ DFN-modell för grundvattenflöde i betydande omfattning ändra på antalet deponeringshål med höga flöden jämfört med DFN-modellerna som presenteras av SKB (2011)?
3. Bildning och persistens av en ”tub” eller ”kanal” genom bufferten med extremt liten diameter som skulle kunna träffa kapselytan diskuterades. Begränsade tillgängliga bevis (Posiva 2009), tyder dock på att även om en sådan kanal skulle bildas (eller uppstå från en defekt vid inplacering av buffertblock), skulle den tätas och inte kvarstå i slutförvarsmiljö.
4. Eventuella effekter av utökade torra förhållanden, där buffertåtermättnad kan ta så lång tid som 6000 år (SKB, 2011), diskuterades också vid workshopen.

Potentialen för kombinationer av alternativa processer eller alternativa modeller / antaganden som skulle kunna ändra SKB:s säkerhetsanalyser togs också upp. Tre möjliga alternativ eller modifieringar av strategin i SR-Site presenterades och diskuterades:

Alternativ 1: Omfattande analys av degraderade säkerhetsindikatorer advektion + mikrober + otillräcklig täthet / självtätning initialt i alla deponeringshål;
Alternativ 2: Alternativ 1 + alternativ DFN (t.ex. alternativ fördelning av flödeshastigheterna Q1, med en högre procentandel av höga Q1-värden);
Alternativ 3: Alternativ 2 + alternativ grundvattenkemi (t.ex. alternativa tolkningar av övre gränser på sulfid / sulfat-koncentrationer och flöden till kapselytan).

Dessa är exempel på ytterligare känslighetsberäkningar som SSM kan göra eller begära från SKB, för att ytterligare testa och bekräfta robustheten i säkerhetsutvärderingar som redovisas i SR-Site (SKB, TR-11-01, 2011).

Slutligen, det noterades upprepade gånger under workshopens presentationer och diskussioner att SKB hade gjort konservativa gränssättande antaganden eller försummat vissa egenskaper, händelser och processer (FEP) som skulle kunna verka för att minska eller eliminera vissa negativa effekter. Motiveringen för att utesluta sådana FEP eller för att göra konservativa gränssättande antaganden verkar vara förknippad med svårigheten att få exakta och korrekta uppgifter för särskilt komplicerade FEP. För att bedöma alternativa antaganden, data och modeller från SKB:s SR-site (TR-11-01), bör icke- kvantifierade konservativa antaganden hållas i minnet när man utvärderar säkerhetsbetydelsen av framställda eventuella konsekvenser.

Projektinformation

Kontaktperson SSM: Clara Anghel
Diarienummer : SSM2014-2834

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) license applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information and provide expert opinion on specific issues. Workshops are organized for the discussion of the current status of SSM's review findings and consultants' opinions reached on particular processes, safety functions and barriers of central importance in SKB's safety assessment SR-Site for a final disposal of spent fuel at Forsmark. The viewpoints and conclusions expressed at the workshops are those of the workshop participants and do not necessarily coincide with those of SSM.

Objectives of the workshop

The objective of this workshop was to bring together experts in the field of general corrosion of copper and to have systematic discussions to identify and consider significant safety impacts on corrosion of copper. The workshop included discussions about the significant impacts of general corrosion of copper canister on (a) number of packages failing by corrosion, and/or (b) early failure times of canisters from higher general corrosion rates (basically the C1 scenario as presented by SKB in SR-Site).

This assignment is part of the review regarding the identification and evaluation of significant safety factors affecting the general corrosion of copper canisters in a KBS-3 repository that could generate eventually containment failure of such canisters. SSM and external experts in the areas of groundwater flow, geochemistry, buffer and materials behavior as well as safety assessment participated in the workshop.

Summary of the workshop

This report describes the outcome of the workshop organized by SSM on general corrosion of copper that was held in Stockholm on the 26-27th of August, 2013. The report summarizes the issues discussed and extracts the essential viewpoints that have been expressed. It should not be considered as a comprehensive record of all the discussions at the workshop and individual statements made by workshop participants should be regarded as opinions rather than SSM's point of view.

Based on the information, arguments and analyses presented in the workshop, it has been concluded that no safety-significant impacts on the general corrosion rate of canisters or the number of canisters failing by corrosion are clearly evident for either intact buffer or eroded buffer situations. The reason for the absence of sensitivity to possible erosion of buffer arises from several factors, most notably from the assumed application of criteria for the rejection of deposition-holes (i.e., rejecting holes with high groundwater inflow rates from fractures).

Low erosion rates would be another mitigating factor regarding the safety-significance of any impacts for the eroded buffer case, especially where extreme speculative alternative models or combinations of alternative models are considered. These erosion rates are expected to be extremely low for the currently reported distributions in fracture flow rates and fracture apertures at Forsmark. Therefore, significant buffer erosion to allow advective flow conditions would only occur in a few deposition holes during a far-future glaciation, at a time when the radioactivity of the spent fuel will have greatly decreased.

Several concerns were raised at the workshop regarding processes or alternative models/ assumptions that might modify SKB's safety analyses.

1. First, the lowering of buffer density in an eroding buffer will allow the onset of microbial activity before the onset of advective flow conditions. The possibility of microbial reduction of dissolved sulphate (at concentrations generally much higher than that for dissolved bisulphide) at the canister surface would raise the rate of general corrosion of canisters in partially eroded buffer conditions (albeit for the same limited number of deposition holes as considered by SKB).
2. A second concern was whether application of an alternative DFN model for groundwater flow might significantly shift the number of deposition holes with high flow rates compared to the DFN models considered by SKB (2011).
3. Formation and persistence of an extremely small-diameter 'tube' or 'channel from the rock interface through the buffer and intersecting the canister surface was the third raised concern. Limited available evidence (Posiva, 2009), however, indicates that even if such a channel were to form (or occur from a defect in emplacement of buffer blocks), it would seal and not persist under repository conditions.
4. Possible impacts of extended dry conditions, where buffer resaturation might take as long as 6000 years (SKB, 2011), were also raised at this workshop.

The potential for combinations of alternative processes or alternative models/ assumptions that might modify SKB's safety analyses was also raised. Three possible alternatives or modifications to the SR-Site approach were presented and discussed:

Alternative 1. Comprehensive analysis of degraded safety function indicators ® advection + microbes + inadequate tightness/self sealing in all deposition holes initially;

Alternative 2. Alternative 1 + alternative DFN (e.g., alternative distribution of flow rates Q1, with a higher percentage of high Q1 values);

Alternative 3. Alternative 2 + alternative groundwater chemistry (e.g., alternative interpretations of upper bounds on sulphide/ sulphate concentrations and fluxes to the canister surface)

These are examples of additional sensitivity calculations that SSM might make or request from SKB, in order to further test and confirm the robustness of the safety-assessments reported in SR-Site (SKB, TR-11-01, 2011). Finally, it was repeatedly noted during the workshop presentations and discussions where SKB had made conservative bounding assumptions or neglected certain features, events and processes (FEP) that would act to mitigate or eliminate certain adverse impacts. The motivation for excluding such reserve FEPs or making conservative bounding assumptions seems to be associated with the difficulty in obtaining precise and accurate data for particularly complex FEPs. Assessing alternative assumptions, data and models from the SKB SR-site, the unquantified conservatisms should be kept in mind when evaluating the safety significance of any derived impacts.

Project information

Contact person at SSM: Clara Anghel

Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Michael Aptedy

INTERA Incorporated / Denver, USA

Technical Note 64

2014:43

Workshop on general corrosion of copper

Main Review Phase

Date: August, 2013
Report number: 2014:43 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Contents

1. Introduction

On August 26-27, 2013 a workshop was held at SSM offices in Stockholm with the purpose of conducting systematic discussions to identify and evaluate significant safety factors affecting the general corrosion of copper canisters in a KBS-3 repository that could generate eventually containment failure of such canisters. This subject basically aligns with the Can 1 safety function, stating that the copper canister should "provide corrosion barrier", as described and analyzed in Chapters 8, 11 and 12 of the SR-Site report (TR-11-01).

Several guidelines were set to focus the discussions in this workshop. These included

- address only on general corrosion failure of copper;
- consider only HS^-, Cl^-, and O_2 as corrodants;
- consider cases for intact buffer, eroding buffer, and bounding "no-buffer"
- consider possible impact of rock spalling;
- assume no alteration to chemical properties of buffer;
- qualitatively consider possible microbial effects on HS^- production;
- assume negligible potential effect of radiation effects on corrosion.

The workshop participants came to the workshop having read TR-10-66, "Corrosion Calculations Report for the Safety Assessment SR-Site", and surveyed the sensitivity-calculations in Chapters 12 and 13 of the SR-Site report, TR-11-01, relevant to their technical areas.

SSM and external experts (list of participants in Appendix 1) in the areas of groundwater flow, site geochemistry, buffer and materials behavior as well as safety assessment participated in the workshop. In each area, overview presentations were made regarding the diverse set of processes and factors that potentially impact the general corrosion of copper canisters. For each of these technical areas affecting general corrosion of copper canisters, the workshop experts were asked to

- identify whether there are credible alternative models, data, or boundary conditions to those presented by SKB that would lie *significantly* outside the bounds presented by SKB in SR-Site;
- estimate potential impacts of any such alternatives on safety functions, boundary conditions or performance from that presented by SKB;
- focus their discussions on the potential safety consequences of such deviations on (1) the ***number of waste packages failing by chemical corrosion***, and/or (2) the ***rate of general corrosion***, and

• recommend specific alternative conceptual models or data to be considered for further safety-evaluation by SSM and/or external safety-assessment experts.

This Technical Note provides a summary of the presentations, discussions and results from this workshop on general corrosion of copper canisters. The following was the order of presentations, with the noted Sections of this Technical Note shown in **[Bolded Brackets]**;

• buffer-behaviour issues (especially on possible buffer erosion) potentially affecting general corrosion of copper canisters **[Section 2]**,

• groundwater-flow issues potentially affecting general corrosion of copper canisters [**Section 3]**, and

• groundwater-chemistry issues potentially affecting general corrosion of copper canisters **[Section 4]**.

These presentations were then followed by a summary **[Section 5]** in which each issue is placed into a safety-assessment context with respect to whether, and to what degree, such issues might significantly and adversely affect long-term safety by changing (1) the ***number of waste packages failing by chemical corrosion***, and/or (2) the ***rate of general corrosion.*** Based on these results, during the workshop recommendations have been made for follow-up analyses by SSM.

2. Buffer Behaviour Potentially Affecting General Corrosion of Copper Canisters

2.1. SKB's presentation

In SKB report TR-10-66 there are three basic cases for the mass-transport behaviour of buffer affecting general corrosion of canisters that have been considered:

- mass-transport for intact buffer with advection in fracture, including consideration of thermally induced rock spalling,
- mass-transport for a partially eroded buffer with advection in fracture, and
- initial advection (buffer absent) in deposition holes.

In addition, Section 12.2 (TR-11-01) addresses the impact of an eroding buffer on general corrosion of copper canisters. Section 12.6 of SR-Site (TR-11-01) addresses the overall analyses related to general corrosion of copper canisters that includes the eroding buffer and buffer-absent cases.

The factors explicitly considered by SKB (page 598, TR-11-01) include

- Copper corrosion modes;
- Diffusive transport of corroding species through the buffer (for intact buffer);
- Advective transport in a deposition hole with an eroded buffer;
- Groundwater flow;
- Groundwater concentrations of sulphide;
- Possibility of oxygen penetration

2.1.1. SKB's Treatment of Chemical Erosion of Buffer

In SKB report TR-11-01, chapter 10.3.11, it is shown that the initial buffer may experience *chemical erosion*, in which buffer material might be removed during glacial periods when dilute melt waters might circulate to repository depths. Loss of buffer mass would translate into decrease in buffer density, which in turn could lead to progressive loss of safety functions of the buffer, including onset of advective flow through the buffer.

With respect to the estimation of the extent of buffer erosion (hence impact transitioning from intact buffer to eroded buffer with lower density and possibly compromised/degraded safety functions), SR-Site analyses include:

- a *quantitative model* for quantifying the extent of erosion given by an empirical erosion rate, $R_{\text{Erosion}} = A \cdot \delta \cdot v^{0.41}$ where v is the groundwater velocity in a fracture intersecting the buffer, δ is the aperture of the intersecting fracture, and A is a fitting constant;

- application of criteria for deposition hole rejection;

- the dilute groundwater composition and concentration (with the concentration of cations expressed as charge $\Sigma q[M^{q+}] < 4$ mM) required for chemical erosion to occur;

- the fraction of time (25%) during the 10^6-year assessment period during which the groundwater has the dilute composition sufficient to enable erosion;

- an assumed hemi-spherical eroded cavity formed within the buffer from the erosion into the fracture;

- the amount of buffer (1200 kg) required to be eroded per deposition hole before advective conditions occur.

SKB report TR-11-01, chapter 12.2 also reports probabilistic sensitivity calculations made regarding changes in these factors to more conservative and/or bounding values (e.g., erosion happening 100% of the time). For its Base Case (semi-correlated base case), SKB calculates 0.6 deposition holes achieving advective flow conditions in the first 10^5 years and 19 deposition holes at the end of the one million year assessment period. In the SR-site it is stated that, while pessimistic estimates and uncertainty bounds on these factors lead to increases in the calculated number of deposition holes with advective flow, less than ten percent of the deposition positions are estimated to reach advective conditions after 10^6 years, even for the most unfavorable cases considered.

2.1.2. SKB's Analysis of Impact of Buffer Erosion and Groundwater Flow on General Corrosion of Canisters

The number of possible eroded/ advective deposition positions must, in turn, be placed into the context on their impact on long-term safety. Regarding calculated safety impacts on canister failure by general corrosion arising for the eroding-buffer and buffer-absent (initial advection) cases, SKB report TR-11-01 (see page 574) states the following:

"For the reference evolution, the mean number of canisters calculated probabilistically to fail during the one million year assessment period due to buffer colloid release/erosion leading to buffer advection and hence enhanced corrosion is 0.12 for the semi-correlated hydrogeological DFN model, see Section 10.4.9. There, it is also demonstrated that the consequences in terms of canister failures are similar (on average 0.17) if ***advection is assumed initially in all deposition positions****. (In both these cases rejection according to EFPC is assumed.)*

This result is important for the treatment of the buffer advection scenario. Irrespective of the outcome of the complex interplay of a number of uncertain factors influencing the occurrence of buffer advection, the consequences in terms of canister failures are always bounded by the case where advection is assumed for all canisters throughout the assessment period, and these failure rates are similar to those for the reference evolution where only a small fraction of the deposition holes are affected by advective conditions in the buffer. The reason for this simplifying circumstance is that the time taken to erode the buffer to the extent that advection occurs is shorter than that required to cause corrosion failure once the advective conditions are established. For both processes, the groundwater flow rate at the deposition position in question is an important determining factor, and dependence on other factors influencing erosion and corrosion, respectively, is such that the time required to reach advective conditions is, in general, shorter than that required to cause corrosion failure once advective conditions are established. It is also noted again that it is only in the small number of holes that have high advective flow rates in the intersecting fractures that erosion and subsequent enhanced corrosion could lead to canister failures in one million years."

A wide range of alternative, conservative assumptions regarding DFN flow, [HS^-], canister geometry, and buffer erosion are calculated by SKB for the buffer-erosion/ advective-flow cases, including combinations of conservative assumptions (SKB reports TR-10-66 and TR-11-01). The maximum number of canisters calculated to fail in the first 10^6 years never exceeds 2 according to SKB's sensitivity analyses (see Figure 12-16, TR-11-01).

2.2. Selection of discussion topics on buffer behaviour

For the assumptions and data applied for the intact buffer case, SKB's analyses showing canisters failures only occurring at extremely long time periods (>>10^5 years) seems defensible. This sets the focus on situations in which buffer may erode or be mis-emplaced, leading to lower buffer density that may compromise or degrade safety features of the buffer. With decreasing buffer density, impacts on buffer performance could include loss of buffer 'tightness' against rock and canister, onset of microbial activity within the lower-density buffer, and eventually onset of advective flow conditions (Figure 1).

Both the rate of buffer erosion and the rheological response of an eroding buffer over extended time periods (> a few years) are uncertain because of obvious practical limitations to the duration of tests. SKB has selected a simplified force-balance model with a higher rate of buffer erosion rather than the alternative, more complex phenomenological model also developed for SKB. Several participants suggested that comparison and possible linkage between these two SKB models could aid in confirmation and confidence in understanding long-term buffer erosion.

A further concern is the uncertainty in buffer response to sustained erosion. As SKB notes (TR-11-01, page 600, 2011), "*A smaller [canister contact-area experiencing advective flow] yields a higher corrosion rate since all incoming sulphide is assumed to react with the exposed canister surface.*" The hemi-spherical assumptions for buffer erosion adopted in SR-Site are rationalized by SKB, but other geometries for advective flow might be envisioned. In particular, the possible occurrence of extremely narrow (hence, small surface area contact with a canister) channels or 'tubes' through or across the buffer has been raised (see Section 3 of this report).

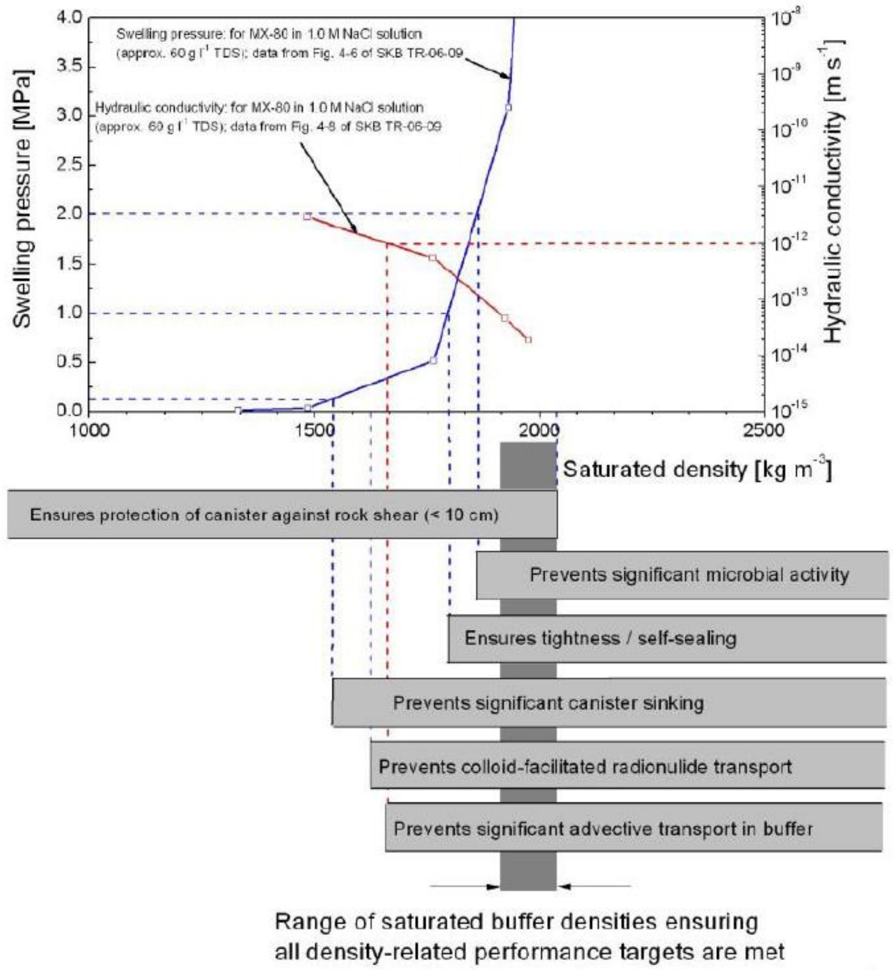

Figure 1. Safety features for compacted bentonite buffer as a function of saturated density from Posiva, 2009, based on the Finnish version of SKB's KBS-3 concept.

2.3. Report of the discussion topics on buffer behaviour

Separate presentations were made by Dr. Göran Sällfors on buffer rheological modelling and by Dr. Randy Arthur on chemical erosion of buffer. The following subsections summarize their presentations and follow-up discussions by the workshop participants.

2.3.1. Rheological Models for Eroding Buffer

Rheology can be defined as the study of matter primarily in the liquid state, but is also applicable to soft solids under conditions of plastic flow. Buffer is composed of bentonite, a natural material containing a significant fraction of smectite clay that swells upon contact with water. Under high compaction, the saturated, high swelling-pressure buffer provides several safety functions in the KBS-3 design, including (1) assurance of diffusive transport of corrodants from the exterior host rock to the surface of the copper canister, (b) impeding the viability of microbial activity within the pore water of the buffer, and (c) assuring tight swelling against both the interior canister and exterior host rock.

The basic properties and behavior of compacted buffer (MX-80 as the current reference) has been well studied by SKB and many international repository programs. Properties such as deformation behavior (swelling properties including swelling pressure), shear strength, hydraulic conductivity, suction, freezing and thawing are reasonably well documented from small- to full-scale tests conducted under controlled laboratory conditions (SKB TR-10-11). Field tests have also been conducted over several years to examine the rate and rheological response of buffer from re-saturation.

With respect to modeling buffer response to erosion, the suite of diverse tests conducted to date have focused mainly on the rate of buffer erosion, with less attention to the temporal and spatial rheological response in the eroded buffer. It is not clear whether the rate of re-adjustment (referred to here as "homogenization") of an eroding saturated buffer is fast relative to realistic rates of erosion (leading to gradual, uniform decrease in buffer density, hence, properties, over the entire buffer), or is slow relative to erosion (leading to comparatively fast, localized loss in buffer density, perhaps even localized void or 'cavity' formation).

SKB (TR-10-66, TR-11-01) modeling of the impact of buffer erosion on general corrosion of canisters assumes a bounding case of the latter situation. No internal readjustment response in the saturated buffer from erosion is assumed, leading to the formation of a large hemi-spherical cavity growing from the rock interface in toward the canister surface (SKB TR-11-01). When this cavity reaches the canister surface, SKB calculates a minimal height (hence minimal surface area and high rate of general corrosion from sulphide transported by advection) consistent with assuming the hemi-sphere stops growing at this time.

Three additional potential factors raised, but not further addressed in this workshop with respect to assessing buffer rheological response to erosion are (1) the potential formation of a spalling zone of rock at the buffer-rock interface, (2) mineralogical changes within the buffer, and (3) extended (up to several 1000's years) delay in the re-saturation of initially emplaced buffer. The possibility of spalling has been factored into SKB's analysis of mass-transport resistance (the inverse of SKB's equivalent flow rate, Q_{eq}) affecting long-term general corrosion rate of the canister (SKB TR-10-66), while the amount of new void space created is negligible with respect to significantly lowering the density of the buffer. Mineralogical changes that could affect rheological behavior of the buffer include re-distribution of minerals in the presence of the initial thermal and humidity gradients across the buffer that arises from radiogenic heating by spent fuel. Also included is possible mineralogical transformation of smectite to non-swelling alteration products (e.g., zeolite). The rheological concern regarding delayed re-saturation is that sustained dry conditions of the buffer for prolonged periods could cause dry-out, cementation and cracking from combined mineralogical reactions and moisture-loss in buffer.

2.3.2. Chemical Erosion of Buffer

SKB's treatment (TR-09-35) of chemical erosion of buffer in dilute glacial melt waters was reviewed with respect to the defined conditions necessary for chemical erosion to occur as well as the laboratory test data used to develop the empirical model for rate of buffer loss used in SR-Site:

$$R_{\text{Erosion}} = A \cdot \delta \cdot v^{0.41}$$

where v is the groundwater velocity in a fracture intersecting the buffer, δ is the aperture of the intersecting fracture, and A is a fitting constant.

Four possible alternatives or modifications to the SR-Site approach were presented and discussed:

The principal point raised was that several other safety features of the intact buffer, such as sustaining tightness between buffer and rock and canister surfaces, and inhibiting microbial activity, would be lost by decreasing density in eroding buffer long before the onset of advective flow conditions (see Figure 1). These potential impacts are not specifically addressed in SKB (TR-11-01) analyses.

In particular, the effect of microbial reduction of dissolved sulphate to sulphide within ingressive groundwater contacting the canister surface could be significant because of the much higher sulphate concentration compared to sulphide concentrations in Forsmark groundwater (see Section 4 of this report). An independent, bounding analyses could be conducted of an eroded buffer, in which sulphate-reducing bacteria (SRB) allow all of the sulphate flux arriving at the canister surface to be transformed to sulphide that then reacts with the copper canister. Because viability of microbial activity arises prior to onset of advective flow conditions for an eroding buffer with decreasing density, both diffusive flux and advective flux conditions could be considered. Both slow buffer homogenization (hemi-spherical cavity development as evaluated in SKB TR-11-01) and rapid buffer homogenization (no cavity development) could be considered as bounding cases.

3. Groundwater Flow Affecting General Corrosion of Copper Canisters

3.1. SKB's presentation

As noted in Section 2, SKB's analyses (SKB TR-10-66, TR-11-01) of canister failure by general corrosion include the effect of equivalent groundwater flow (or its inverse, mass-transfer resistance). SKB adopts a simplified force-balance model empirically fit to test data for the rate of buffer-mass loss as related to groundwater flow in adjoining fractured host rock

$$R_{\mathrm{Erosion}} = A \cdot \delta \cdot v^{0.41}$$

where v is the groundwater velocity in a fracture intersecting the buffer, δ is the aperture of the intersecting fracture, and A is a fitting constant.

With respect to the importance of advective flow affecting the erosion rate of buffer, hence the failure rates of canisters by general corrosion, SKB (TR-11-01, page 574) states

"*Irrespective of the outcome of the complex interplay of a number of uncertain factors influencing the occurrence of buffer advection, the consequences in terms of canister failures are always bounded by the case where advection is assumed for all canisters throughout the assessment period, and these failure rates are similar to those for the reference evolution where only a small fraction of the deposition holes are affected by advective conditions in the buffer. The reason for this simplifying circumstance is that the time taken to erode the buffer to the extent that advection occurs is shorter than that required to cause corrosion failure once the advective conditions are established. For both processes, the groundwater flow rate at the deposition position in question is an important determining factor, and dependence on other factors influencing erosion and corrosion, respectively, is such that the time required to reach advective conditions is, in general, shorter than that required to cause corrosion failure once advective conditions are established. It is also noted again that it is only in the small number of holes that have high advective flow rates in the intersecting fractures that erosion and subsequent enhanced corrosion could lead to canister failures in one million years.*"

Therefore, the importance of groundwater flow boundary conditions in the host rock are two-fold, (1) only a small number of deposition holes are expected to have groundwater velocities sufficient to cause significant buffer erosion (and enhanced corrosion rate) in the first 10^6 years, and (2) the same exceptionally low groundwater velocity indicates an exceptionally high mass-transfer resistance (the inverse of equivalent groundwater flow rate) that constrains and limits the transport rate of dissolved sulphide from the rock into the buffer (or even into an open cavity having advective flow).

3.2. Selection of discussion topics on groundwater flow

Given the high safety importance SKB asserts for groundwater flow rate (or perhaps more accurately, the high mass-transfer resistance to flow asserted for the host rock at Forsmark) in its assessment of long-term, general corrosion of canisters, it is deemed prudent to examine credible, alternative sparse channel-network models to those used by SKB in their discrete fracture network (DFN) representation of the Forsmark site. In particular, alternative flow models that would indicate considerably higher number of deposition holes having significantly higher flow rates need to be evaluated to determine if these deviations would lead to the expectation of either a greater number of deposition holes experiencing buffer erosion, a greater rate of buffer erosion, or both. Credibly higher advective flow rates might also directly affect confidence in SKB's bounding analyses for the 'initial advection (buffer absent) case', and SKB's assertion that

"*…, the consequences in terms of canister failures are always bounded by the case where advection is assumed for all canisters throughout the assessment period, and these failure rates are similar to those for the reference evolution where only a small fraction of the deposition holes are affected by advective conditions in the buffer.*"

3.3. Report of the discussion topics on groundwater flow

Presentations on SKB's DFN and equivalent flow (Q_{eq}) models were presented by Drs. Joel Geier and Stuart Stothoff, respectively. These presentations and associated discussions are summarized in the following sub-sections.

3.3.1. Alternatives to SKB's DFN Modelling

A general overview of the data and models used by SKB to support their estimates of groundwater flow at deposition holes was presented. The regional driving force for flow at the Forsmark site is controlled by the local, relatively flat-lying topography and, to a lesser extent, density contrasts between meteoric water and Baltic Sea water.

A schematic representation of major water-bearing discontinuities at the Forsmark site is shown in Figure 2. Data on groundwater flow in hydraulic conductor domains (HCD, the larger-scale deformation zones and near-surface fractures/sheet-joints) are derived from reasonably well-characterized pumping tests from deep boreholes. There is uncertainty in trends of flow at depth because of limited number of measurements for HDCs.

SKB itself has considered numerous alternative DFN models. The DFN modelling by SKB relates to the flow modelling interpretation closer to, and inclusive of, the underground workings and deposition holes for the proposed repository. At this time, the geometry for fractures in the DFN models are based on surface outcrop measurements, while the intensity/ frequency of such fractures is based on borehole mapping. The sub-set of fractures that are found to be conductive to groundwater flow are mapped and characterized by flow logging (PFL) and packer testing. Calibrations of differing DFN models to PFL data are made using alternative size-transmissivity relationships, while fracture apertures are derived from generic correlations to transmissivity measurements. It was noted that there is only poor resolution for low-transmissivity features, which constitute up to 90% of the rock at Forsmark. Furthermore, SKB's DFN models are not well characterized by pumping tests or geochemical sampling.

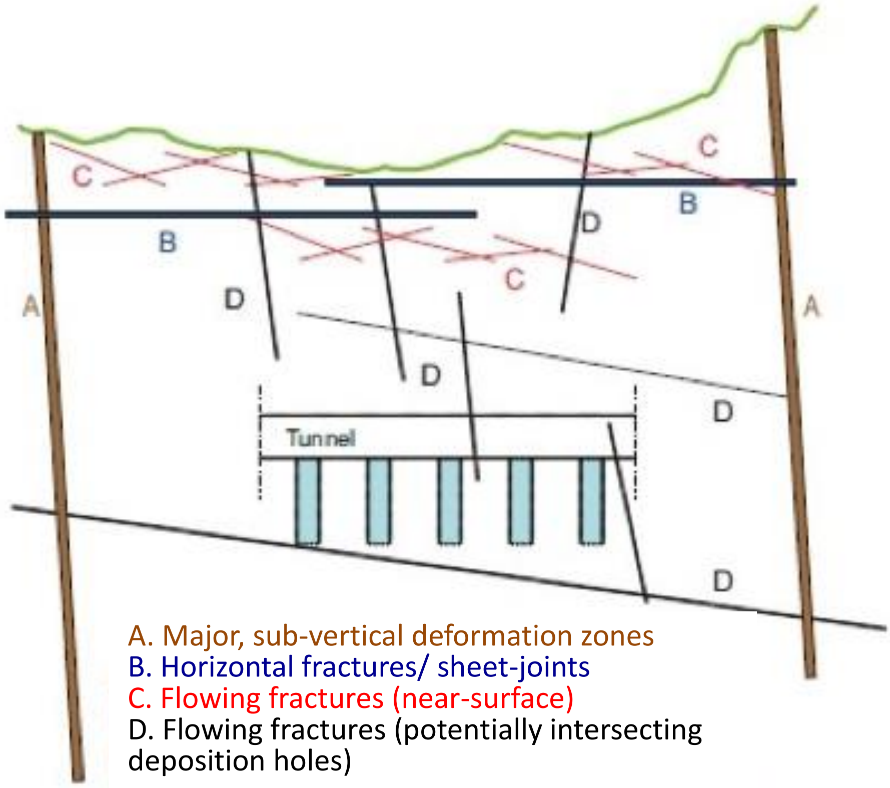

Figure 2. Schematic representation of the types of major water-baring features at Forsmark. (source: J. Geier)

For site-scale models of groundwater flow, SKB couples its 'local-scale' DFN models to the larger-scale HCD models to develop an equivalent continuous porous medium (ECPM) model. Flows to the deposition holes are model by SKB's DFN models, constrained by the boundary conditions imposed by its site-scale model.

As an example of an alternative DFN model, so-called 'halo' models have been evaluated in which there are more hydrologically 'tight' deposition holes, but higher (by perhaps as much as 1 to 2 orders of magnitude) flow for the smaller percentage of deposition holes that do see flow. Figure 3 compares several different conceptual DFN models with respect to the fraction of deposition holes vs. the calculated flow into that deposition hole. Other alternative DFN conceptual models, such as sparse channel network (Black et al, 2007), would be expected to yield significantly higher flow into a fraction of deposition holes if applied to the Forsmark site. The other concern regarding this sparse-channel conceptual model is whether narrow channels (rather than planar fractures) intersecting a deposition hole would lead to a phenomenologically different model for chemical erosion of buffer.

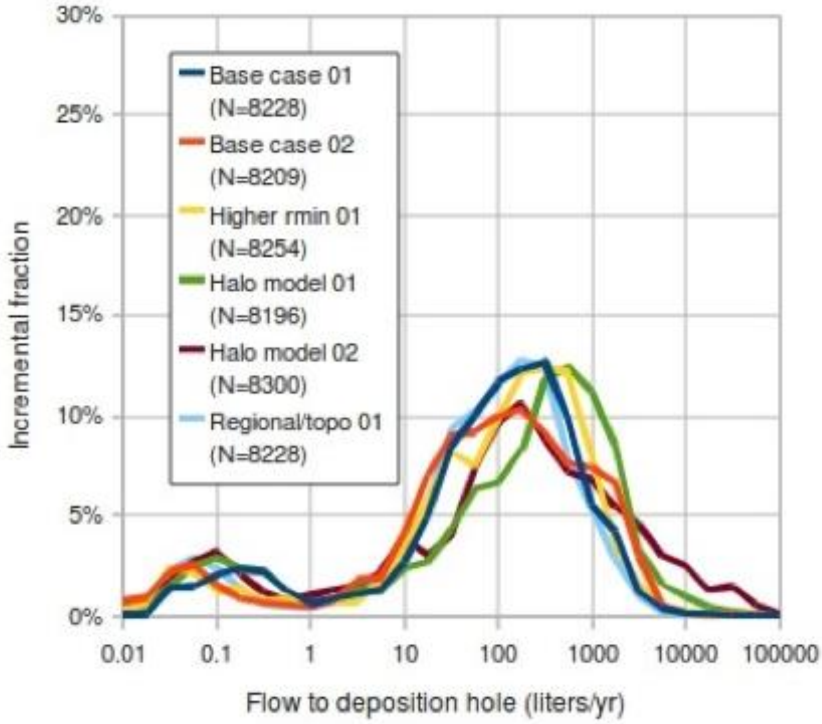

Figure 3. Histogram representation of predicted fracture flow rates for different conceptual DFN models of the Forsmark site (source: Geier, 2011, SSM report 20011:13)

A final concern that was raised was SKB's assumed favourable implementation of criteria for deposition hole rejection (SKB, TR-11-01, page 578). Application of such criteria, by definition, truncates deposition holes that might have both higher groundwater flow rates and potential for faster buffer erosion. It was recommended that a separate study or workshop be devoted to the confidence in SKB's ability to develop and apply such criteria for deposition hole rejection.

3.3.2. Analysis of SKB's Q_{eq} Modelling

SKB characterizes transfer of dissolved species to and from the canister in terms of effective diffusion rates, using the Q_{eq} concept (SKB TR-10-66, TR-09-35). In the Q_{eq} approach, the mass-transfer resistance of solute flux from the fracture into the buffer can be noted as Q_1, in which the corrodants are assumed to be radially transported from the fracture aperture through the buffer to the canister surface. The mass-transfer resistance of the buffer itself can be denoted as Q_2. Such mass-transfer resistances, *R*, in series are summed inversely to calculate a Q_{eq};

$$R = 1/ Q_{eq} = 1/ Q_1 + 1/ Q_2$$

If the rock at the rock-buffer spalls, this is assumed to lead to parallel transport pathways of corrodants from the rock/fracture interface through the buffer to the canister surface (SKB, TR-10-66).

SKB's Q_{eq} model is generally controlled by either fracture (Q_1) or buffer (Q_2) mass-transfer resistances (only jointly important when $Q_1 \approx Q_2$). For the data and assumptions made in SKB (TR-10-66, TR-11-01), Q_{eq} is dominated by fracture properties (i.e., $Q_{eq} \approx Q_1$), and only for cases with significant spalling do the transport properties of the buffer become important.

The total mass-flux of corrodants (e.g., HS^-) from the fracture through the buffer to the canister surface is equal to the product of Q_{eq} and concentration gradient of HS^-, (i.e., the difference in HS^- concentration in the fracture and the HS^- concentration at the canister surface). Since SKB assumes the HS^- is instantaneously consumed by reaction with Cu, the effective concentration gradient equals the HS^- concentration in the fracture. Because of the assumed zero concentration for HS^- due to instantaneous reaction at the canister surface, the calculated general-corrosion rate for a fracture aligned with the top (or bottom) of a canister is approximately a factor of 2 greater than for a fracture aligned with the mid-point of the canister.

The hypothesis of formation of small aperture 'channels' or 'tubes' through the buffer was discussed. If the cross-sectional area of such pipes/ tubes remained small where it contacted the canister surface, then the advective flux of HS^- to the canister surface might be sufficient to lead to general-corrosion failure at that localized spot in time periods less than 100,000 years.

This hypothesis speculates on formation of such a channel/tube arising from initial flow along the incompletely sealed 'seam' between two buffer disks. Assuming such channels/ tubes could be formed, the swelling of the buffer disks would act to close the channels/tubes. The persistence of small diameter pipes/tubes through the buffer would require sustained erosion of clay to compensate for such swelling; on the other hand, increasing flow velocity would tend to widen the cross-sectional area of such channels/tubes, enlarging their contact area on the canister surface, and mitigating the increase in general corrosion rate.

Experimental evidence whether such pipes/tubes can form and persist was discussed. No evidence for the spontaneous formation of such through-going tubes in buffer under simulated repository conditions was identified. Discussion then turned to studies on the closure of cavities/ tube-like structures in bentonite materials. Interesting tests on swelling around cavities and voids conducted by SKB were noted, although not on channel/tube geometry features (TR-12-02). Tests on swelling and closure of a tube-like hole, artificially created, have been recently reported (Posiva, 2012). In these tests, done on backfill (bentonite + aggregate mix, rather than pure bentonite buffer) material, an initially artificially generated channel with a 5-mm diameter was shown to self-heal. However, the material filling the original tube had a somewhat increased hydraulic conductivity compared to the bulk material. The exact hydraulic pressure gradients during the tests were not reported. It was indicated that the pressures were kept low, but still high enough to cause measurable water amounts to initially flow through the tube before closure. In conclusion, these tests indicated that swelling of bentonite material would likely heal any initial tube, unless the pressure gradients are large. However, once the buffer is fully saturated and plugs are installed along the emplacement tunnel, pressure gradients are expected to be comparatively small around deposition holes.

4. Groundwater Chemistry Affecting General Corrosion of Copper Canisters

4.1. SKB's presentation

SR-Site (SKB TR-11-01) considers the general corrosion of copper canisters from several sources of corrodants. Initial corrodants sources in buffer and backfill (i.e., O_2 trapped in pores and trace minerals such as pyrite and organic matter) are shown to give at most a small contribution to copper corrosion (SKB TR-11-01Sections 10.2.5, 10.3.13 and 12.6.2).

Corrosion by O_2 from possible deep circulation of dilute glacial melt waters is also analysed by SKB (TR-10-66, TR-11-01). SKB described that the degree of oxygen penetration to depth for steady state flow conditions will be controlled by (i) duration of the episode, (ii) concentration of oxygen at the inlet of the flow paths, (iii) extent to which microbial processes contribute to oxygen consumption, (iv) surface area of reactive minerals in the rock and their reaction kinetics with oxygen, and (v) the transport properties of the recharge flow paths that connect the surface to the deposition holes. For the case of intact buffer (corrosion for diffusive conditions), SKB (TR-10-66, TR-11-01) presented analyses that show limits on both the duration (1000 years) and number of deposition holes that might experience elevated dissolved O_2 concentrations (31 deposition holes with O_2 concentrations ranging from 0.1 to 1.5 mM). Certain inorganic and biological processes were mentioned in this workshop that could attenuate and deplete dissolved O_2 from groundwater passing downwards through soil, sediments and Fe^{2+}-bearing minerals in fractures. These processes were not fully covered in SKB's analysis. SKB concludes from its assessment that corrosion due to oxygen penetration under diffusive-transport in deposition holes is negligible.

SKB also analysed canister corrosion by deep circulation of oxygenated water for advective conditions in the buffer (SKB TR-10-66, TR-11-01). The same mass-transport formulation and constraints as applicable for corrosion by HS^- (Section 3) were applied to the O_2 analyses. While higher amounts of corrosion by O_2 were calculated for advective conditions in the buffer compared to diffusive conditions, no canister failures are predicted to occur because of constraints imposed by mass-transfer resistance of the fracture, limited duration and limited maximum concentration (solubility limit) for dissolved O_2. As with the diffusive transport case, the advective transport case neglected inorganic and biological processes that could possibly attenuate and deplete dissolved O_2 from groundwater in natural systems.

SKB is stating that the corrosion of copper by dissolved chloride requires simultaneous conditions of pH<4 and chloride concentration, $[Cl^-]$, > 2M. Paleohydrogeological data from Forsmark, geochemical modelling of 'what if' changes in atmospheric CO_2 concentrations, and characterization of ambient groundwater compositions at Forsmark are used by SKB (TR-11-01 Sections 8.3.4 and 12.6.2) to argue that such conditions do not exist now nor could they arise in the future at the Forsmark site.

This leaves the mass-transfer of dissolve sulphide, HS^-, in Forsmark groundwater as the primary, long-term corrodant that affects the general corrosion of copper canisters. SKB (TR-10-66, equation 4-17) defines the long-term general corrosion rate of copper canisters by HS^- (N_{HS}) as:

$$N_{HS} = Q_{eq} \bullet [HS^-] \bullet t$$

where Q_{eq} is the total equivalent flow rate (typically constrained by and co-equal to the equivalent flow rate in the intersecting fracture to the deposition hole, Q_1), $[HS^-]$ is the concentration of HS^- in the groundwater in the fracture, and t is the time under evaluation.

SKB notes (TR-11-01, page 607),

"…canister failures occur only when the highest flow rates are combined with the highest sulphide concentrations, and when both these entities are pessimistically assumed to be constant in time over the entire one million year assessment period for a given deposition hole."

SKB (TR-11-01) reports the collected measurements of sulphide concentrations at Forsmark (Figure 4). The selection of a representative distribution of HS^- concentration, $[HS^-]$, is made by an extended data quality classification approach. For sensitivity analyses, SKB considers a case in which the highest $[HS^-]$ of $1.2 \bullet 10^{-4}$ M is excluded from the distribution (as being due to transient perturbations and exceeding FeS saturation), a case in which a point twice the highest concentration (i.e., $[HS^-] = 2.4 \bullet 10^{-4}$ M] is included in the distribution, and a case where the mean value of concentration distribution, $[HS^-] = 5 \bullet 10^{-6}$ M, is applied to each deposition hole.

The maximum sulphide concentration is assumed by SKB to be limited by the availability of dissolved Fe^{2+}, leading to the precipitation of FeS phases (SKB TR-11-01). Limited mineralogical data as well as pH and redox modelling presented for the Forsmark site (SKB TR-11-01) suggests a concentration of $Fe^{2+} \geq 10^{-6}$ M. Assuming FeS equilibrium, this would constrain $[HS^-]$ to be between 10^{-5} and 10^{-6} M. The absence or possible depletion of dissolved Fe^{2+} in groundwater would permit higher $[HS^-]$.

With respect to evaluating possible activity of sulphate-reducing bacteria (SRB), SKB (TR-11-01) asserts that the dissolve organic carbon (DOC) concentration of 10^{-4} M (moles/L) is not available for reduction of sulphate, and that fluxes of CH_4 and H_2 at the site are insignificant. The organic carbon contained in buffer and backfill materials are asserted as being unreactive toward sustaining microbial activity.

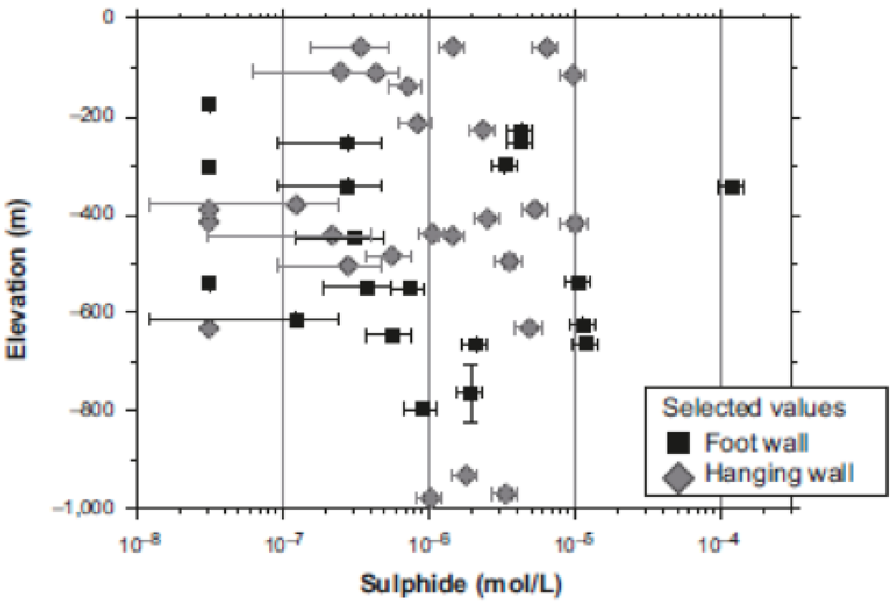

Figure 4. Selected set of measured sulphide concentrations for the Forsmark site at depths below 50 meters. Figure 10-41, SKB, 2011.

4.2. Selection of discussion topics on groundwater chemistry

As noted in Section 3 of this report, the corrosion rate of copper canisters will scale proportionally to the [HS^-] as controlled by mass-transport from the fractured host rock through the buffer. While the SKB (TR-11-01) sensitivity analyses show extremely long (>1 million years) times for canister failure for mean values of [HS^-], measured peak concentrations from rare locations at Forsmark and the Olkiluoto site in Finland (also under consideration for geological disposal) can be 10-20 times higher than the derived mean [HS^-] value. Additional factors such as microbial activity in eroding buffer (including availability of necessary energy and nutrient sources) and concerns regarding the availability Fe^{2+} and the assumption of FeS solubility limits also need to be considered in the set of constraints assumed by SKB.

4.3. Report of the discussion topics on groundwater chemistry

Presentations were made by Dr. Jude McMurray on redox reactions affecting the deep circulation of oxygenated groundwater possibly arising during glacial 'standstill' periods, and by Dr. Adrian Bath on chemical composition and salinity trends in Forsmark groundwater, ranges and controlling mechanisms for HS^- concentrations, and possible penetration of dilute (< 4millimoles/ liter) groundwater to repository depths during a far glaciation that would enable chemical erosion of buffer to be feasible.

The data set collected to date for both HS^- and Fe^{2+} at Forsmark is not as extensive as for other groundwater components. Furthermore, reliable measurement of redox (Eh) for in situ conditions can be difficult to make, and prone to contamination (although such contamination would likely raise the as-measured value).

The assumption that a maximum [HS^-] will be set by FeS precipitation was discussed. The preponderance of [HS^-] measurements are consistent with the predicted FeS solubility-limited concentration. The few elevated [HS^-] measurements could arise from the local absence of $Fe2^+$ in association with SRB activity. Further explanation and evidence from SKB might help to understand and interpret the few anomalously high measurements of [HS^-]. The availability of energy and nutrient sources could act as constraints on the viability of SRB in the rock and buffer.

The role of microbial viability in the SR-Site assessment of maximum [HS^-] is unclear. SKB's focus on the consequence of decreasing buffer density from erosion to enable advective flow ought to also consider the potential onset of microbial viability in eroded buffer, which would likely arise prior to the onset of advection (Figure 1). There may be regions with limited availability of dissolved Fe^{2+}, so that the FeS solubility-limit would not play a significant role. Therefore, in such a case with lowered buffer density enabling microbial activity, the maximum reduced sulphide at the canister surface might be set by the flux of dissolved sulphate to that surface, which could be higher than the flux of dissolved sulphide. This might be a variant or residual case for which SKB could present further evidence and analyses.

5. Safety Significance of Credible Alternative Assumptions, Data and Models Affecting General Corrosion of Copper Canisters

5.1. Approach for the concluding discussions on topics with safety significance

The stated purpose of this workshop was to identify whether there are credible alternative assumptions, data or models to those presented by SKB (TR-11-01) that would lie *significantly* outside the bounds presented in their safety analyses. The earlier section of this report address questions and concerns regarding certain deviations from the SKB (TR-11-01) safety assessment in the areas of buffer behavior, groundwater flow and groundwater chemistry.

In the concluding session of the workshop, the SSM staff and external experts were asked to provide estimates of potential *safety significant* impacts of such deviations on safety functions, boundary conditions or performance of SKB's multiple barrier repository system. The multiple barrier aspect of the KBS-3 design, with many overlapping safety functions of the different barriers, was repeatedly stressed as an important context during these discussions. This is because degradation (or even failure) of one or more safety functions of individual barriers need not necessarily indicate a lack of robust safety performance of the *repository system* due to such impacts.

In addition, the discussion on safety significance for general corrosion of canisters specifically focused on the potential safety consequences of such deviations on (1) the ***number of waste packages failing by chemical corrosion***, and/or (2) the ***rate of general corrosion***. The former aspect is of particular importance, as peak dose rates will scale proportionally with the number of packages that will release radionuclides after failure of the canisters. While canister failures occurring earlier than considered by SKB in their SR-Site safety analyses are also of concern, it was noted that the peak release rate of a canister failing at 10,000 years is only about a factor of 1.2 higher than the peak release rate for a canister occurring at 100,000 years (SKB TR-11-01 Figure 13-53, page 705). That is to say, peak release rate is not proportional to changes in 'time of canister failure'. This because most of the short-lived (half-lives less than about 5000 years) radionuclides will have significantly decayed after 10,000 years containment, while the remaining radionuclides that would contribute to long-term dose rate (e.g., I-129, Cs-135, Np-237) all have half-lives much longer than 100,000 years.

A final aspect of the safety significance review was for the workshop participants to recommend specific alternative assumptions, conceptual models or data affecting general corrosion of canisters to be safety-evaluated by SSM and/or external safety-assessment experts. The purpose of such ancillary calculations would be to confirm and provide confidence in the expert judgments that such alternatives would not lead to calculated release rate behavior significantly outside of the range presented and defended by SKB in their SR-Site analyses. These results and recommendations are summarized in the follow sub-section.

5.2. Summary of the workshop

Tables 1 to 6 summarize the results from the round-table discussions on the several specific issues and concerns raised in the workshop by SSM staff and external experts. The broad conclusion is that no safety-significant impacts on the general corrosion rate of canisters or the number of canisters are clearly evident for either intact buffer or eroded buffer situations.

This reason for the absence of sensitivity to possible erosion of buffer arises from several factors, most notably from the assumed application of criteria for deposition-hole rejection (i.e., rejecting holes with high groundwater inflow rates from fractures, Q_1). Successful implementation of such criteria would impose a truncated distribution of Q_1 (hence Q_{eq}) for deposition holes with emplaced waste packages, skewed to low Q_1 values. Because the general corrosion rate will scale proportionally with Q_{eq}, it is appropriate to reiterate SKB's analysis of general corrosion rate of canisters SKB (TR-11-01, page 574) is based on a bounding case where advection is assumed for all canisters throughout the assessment period (see section 3.1 of this report).

Low erosion rates would be another mitigating factor regarding the safety-significance of any impacts for the eroded buffer case, especially where extreme speculative alternative models or combinations of alternative models are considered. These erosion rates are expected to be extremely low for the currently reported distributions in fracture flow rates and fracture apertures at Forsmark. Therefore, significant buffer erosion to allow advective flow conditions would only occur in a few deposition holes during a far-future glaciation, at a time when the radioactivity of the spent fuel will have greatly decreased.

Several concerns were raised at the workshop regarding processes or alternative models/ assumptions that might modify SKB's safety analyses. First, the lowering of buffer density in an eroding buffer will allow the onset of microbial activity before the onset of advective flow conditions. The possibility of microbial reduction of dissolved sulphate (at concentrations generally much higher than that for dissolved bisulphide) at the canister surface would raise the rate of general corrosion of canisters in partially eroded buffer conditions (albeit for the same limited number of deposition holes as considered by SKB). A second concern was whether application of an alternative DFN model for groundwater flow might significantly shift the number of deposition holes with high Q_1 compared to the DFN models considered by SKB (TR-11-01). Formation and persistence of an extremely small-diameter 'tube' or 'channel from the rock interface through the buffer and intersecting the canister surface was the third raised concern. Limited available evidence (Posiva, 2009), however, indicates that even if such a channel were to form (or occur from a defect in emplacement of buffer blocks), it would seal and not persist under repository conditions.

Possible impacts of extended dry conditions, where buffer re-saturation might take as long as 6000 years (SKB TR-11-01), were also raised at this workshop. It was judged that a separate workshop with a revised set of SSM staff and external experts might be the most appropriate venue to evaluate this alternative scenario, which is not fully considered in SKB (TR-11-01). The reason for a separate workshop with a revised set of experts could be considered to couple thermal-hydrological-mechanical-chemical impacts, which were outside the technical scope of this workshop that focused on general corrosion of copper.

The potential for combinations of alternative processes or alternative models/ assumptions that might modify SKB's safety analyses was also raised. Three possible alternatives or modifications to the SR-Site approach were presented and discussed:

> **Alternative 1**. Comprehensive analysis of degraded safety function indicators$\rightarrow$ advection + microbes + inadequate tightness/self sealing in all deposition holes initially;
>
> **Alternative 2**. Alternative 1 + alternative DFN (e.g., alternative distribution of flow rates Q1, with a higher percentage of high Q_1 values);
>
> **Alternative 3**. Alternative 2 + alternative groundwater chemistry (e.g., alternative interpretations of upper bounds on sulphide/ sulphate concentrations and fluxes to the canister surface)

These are examples of additional sensitivity calculations that SSM might make or request from SKB, in order to further test and confirm the robustness of the safety-assessments reported in SR-Site (SKB TR-11-01).

Finally, it was repeatedly noted during the workshop presentations and discussions where SKB (TR-11-01) had made conservative bounding assumptions or neglected certain features, events and processes (FEPs) that would act to mitigate or eliminate certain adverse impacts. The motivation for excluding such FEPs or making conservative bounding assumptions seems to be associated with the difficulty in obtaining precise and accurate data for particularly complex FEPs. Assessing alternative assumptions, data and models from the SKB SR-site (TR-11-01), the unquantified conservatisms should be kept in mind when evaluating the safety significance of any derived impacts.

6. References

Dueck, A., Goudarzi, R., Börgesson, L., 2012, SKB TR-12-02, Buffer homogenisation, status report, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Geier, J., 2011 , Investigation of Discrete-Fracture Network Conceptual Model Uncertainty at Forsmark, SSM report 2011:13.

Neretnieks, I., Liu, L., Moreno, L., 2009, SKB TR-09-35, Mechanisms and models for bentonite erosion, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Posiva (Schatz, T. & Martikainen, J.), 2009, TKS-2009, Nuclear Waste Management at Olkiluoto and Loviisa Power Plants Review of Current Status and Future Plans for 2010–2012, Posiva Oy, Eurajoki, Finland.

Posiva, 2012, Laboratory Tests and Analyses on Potential Olkiluoto Backfill Materials, Posiva Oy, Eurajoki, Finland.

SKB TR-10-66, 2010, Corrosion calculations report for the safety assessment, SR-Site, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB TR-11-01, 2011, Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of SR-Site project (3 volumes), SR-Site, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

List of participants

Mick Apted	INTERA Inc.
Randy Arthur	INTERA Inc.
Adrian Bath	Intellisci
Mike Egan	SSM
Jan Linder	SSM
Georg Lindgren	SSM
Jinsong Liu	SSM
Jude McMurry	Southwest Research Institute
Göran Sällfors	Chalmers University
Lena Sonnerfelt	SSM
Stuart Stothoff	Southwest Research Institute
Bo Strömberg	SSM
Wei Zhou	INTERA Inc.
Shulan Xu	SSM
Clara Anghel	SSM

Table 1. Impact of high bisulphide, HS^-, concentration in fracture groundwater.

Topic	Intact Buffer		Eroding Buffer	
	Change in Number of Canister Failed	**Change in General Corrosion Rate**	**Change in Number of Canister Failed**	**Change in General Corrosion Rate**
High [HS^-] (i.e., above solubility limit for FeS) found in limited locations, possibly due to lack of Fe^{2+}.	No impact, SR-Site assumes all deposition holes with intact buffer to be experiencing general corrosion by flux of [HS^-] through buffer.	The general corrosion rate will remain set by [HS^-] in rock.	No impact, the number of deposition holes experiencing erosion does not depend on [HS^-].	Same as for Intact Buffer Case, but possible microbial activity within buffer combined with advective transport of SO_4^{2-}.
Safety Significance	Safety significant deviation from SR-Site analyses not likely. • High [HS^-] value considered in range of SR-Site sensitivity calculations.	Safety significant deviation from SR-Site analyses not likely. • General corrosion rate will scale proportionally to [HS^-] value in host rock; SR-Site considers higher [HS^-] in corrosion rate calculations. • Further inquiry regarding origin and persistence of the few anomalously high [HS^-] measurements may be warranted, especially with respect to implications for availability of energy and nutrients sources for microbes.	Safety significant deviation from SR-Site analyses not likely.	Eroded buffer could only arise for a small number of deposition holes at the end of the next glaciation, greatly reducing any possible safety impacts. Possible impact: SRB activity arising in eroding buffer, allowing flux of SO_4^{2-} to canister surface to be rate determining. Supplemental analyses should consider (1) adequacy of energy and nutrient sources in eroded buffer for microbial activity; (2) corrosion rate will scale proportionally with [SO_4^{2-}] in rock.

Table 2. Impact of formation of eroded 'channels' through buffer.

Topic	**Intact Buffer**		**Eroding Buffer**	
	Change in Number of Canister Failed	**Change in General Corrosion Rate**	**Change in Number of Canister Failed**	**Change in General Corrosion Rate**
Focused penetration through buffer, with small contact area on canister, leading to high, localized HS^- flux, hence high general corrosion rate.	Not applicable.	Not applicable.	No evidence for spontaneously occurrence of such penetrations (tubes, channels) through buffer, and limited experimental evidence show that artificially generated channels rapidly seal. High-pressure conditions necessary for hypothetical formation will be eliminated by emplacement of seals/plugs during operations phase.	No evidence for spontaneously occurrence of such penetrations (tubes, channels) through buffer, and limited experimental evidence show that artificially generated channels rapidly seal. High-pressure conditions necessary for hypothetical formation will be eliminated by emplacement of seals/plugs during operations phase.
Safety Significance	No safety significant deviation from SR-Site analyses.	No safety significant deviation from SR-Site analyses.	Safety significant deviation from SR-Site analyses not likely. Further confirmatory tests to demonstrate an understanding of processes and boundary conditions for possible formation and persistence of small channels through buffer could be part of future RD&D commitments by SKB.	Safety significant deviation from SR-Site analyses not likely. Further confirmatory tests to demonstrate an understanding of processes and boundary conditions for possible formation and persistence of small channels through buffer could be part of future RD&D commitments by SKB.

Table 3. Impact of alternative DFN flow model(s).

Topic	**Intact Buffer**		**Eroding Buffer**	
	Change in Number of Canister Failed	**Change in General Corrosion Rate**	**Change in Number of Canister Failed**	**Change in General Corrosion Rate**
Alternative DFN model(s), leading to possibly higher fracture flow (Q_1) in a larger number of deposition holes	[HS^-] in fracture is assumed by SKB to be fixed, not depending on fracture flow rate. Alternative DFN flow models not likely to change number of high Q_1 deposition holes by more than a factor of ~2.	Corrosion rate will scale proportionally with Q_{eq}, which likely will be approximately equal to Q_1. Q_1 for alternative DFN models is expected to change by no more than 1 to 2 orders of magnitude for a small percentage of deposition holes. Furthermore, [HS^-] in fracture is assumed by SKB to be fixed, not depending on fracture flow rate. Also a wide, higher range of [HS^-] are evaluated in SR-Site.	[HS^-] in fracture is assumed by SKB to be fixed, not depending on fracture flow rate. Alternative DFN flow models not likely to change number of high Q_1 deposition holes by more than a factor of ~2.	Corrosion rate will scale proportionally with Q_{eq}, which likely will be approximately equal to Q_1, even for eroded buffer case. Q_1 for alternative DFN models is expected to change by no more than 1 to 2 orders of magnitude for a small percentage of deposition holes. Furthermore, [HS^-] in fracture is assumed by SKB to be fixed, not depending on fracture flow rate. Also a wide, higher range of [HS^-] are evaluated in SR-Site.
Safety Significance	Safety significant deviation from SR-Site analyses not likely. Sensitivity calculations could be made once a credible alterative DFN model can be shown to lead to higher fracture flow (Q_1) in a larger number of deposition holes.	Safety significant deviation from SR-Site analyses not likely. Sensitivity calculations could be made once a credible alterative DFN model can be shown to lead to 10-100 times higher fracture flow (Q_1) in a small number of deposition holes.	Safety significant deviation from SR-Site analyses not likely. Eroded buffer could only arise for a small number of deposition holes at the end of the next glaciation, greatly reducing any possible safety impacts. Sensitivity calculations could be made once a credible alterative DFN model can be shown to lead to higher fracture flow (Q_1) in a larger number of deposition holes.	Safety significant deviation from SR-Site analyses not likely. Eroded buffer could only arise for a small number of deposition holes at the end of the next glaciation, greatly reducing any possible safety impacts. Sensitivity calculations could be made once a credible alterative DFN model can be shown to lead to 10-100 times higher fracture flow (Q_1) in a small number of deposition holes.

Table 4. Impact of duration of buffer erosion.

Topic	Intact Buffer		Eroding Buffer	
	Change in Number of Canister Failed	**Change in General Corrosion Rate**	**Change in Number of Canister Failed**	**Change in General Corrosion Rate**
Extend duration of conditions enabling buffer erosion.	Not applicable.	Not applicable	SKB (2011, page 574) states "*...the consequences in terms of canister failures are always bounded by the case where advection is assumed for all canisters throughout the assessment period, and these failure rates are similar to those for the reference evolution where only a small fraction of the deposition holes are affected by advective conditions in the buffer. The reason for this simplifying circumstance is that the time taken to erode the buffer to the extent that advection occurs is shorter than that required to cause corrosion failure once the advective conditions are established.*"	SKB (2011, page 574) states "*...the consequences in terms of canister failures are always bounded by the case where advection is assumed for all canisters throughout the assessment period, and these failure rates are similar to those for the reference evolution where only a small fraction of the deposition holes are affected by advective conditions in the buffer. The reason for this simplifying circumstance is that the time taken to erode the buffer to the extent that advection occurs is shorter than that required to cause corrosion failure once the advective conditions are established.*"
Safety Significance	No safety significant deviation from SR-Site analyses.	No safety significant deviation from SR-Site analyses.	Safety significant deviation from SR-Site analyses not likely.	Safety significant deviation from SR-Site analyses not likely.

Table 5. Impact of early, deep circulation of dilute groundwater enabling buffer erosion.

Topic	**Intact Buffer**		**Eroding Buffer**	
	Change in Number of Canister Failed	**Change in General Corrosion Rate**	**Change in Number of Canister Failed**	**Change in General Corrosion Rate**
Earlier than expected penetration of dilute (~<4 mmol/L limit) groundwater to repository depths, sufficient to enable buffer erosion to begin.	Not applicable.	Not applicable.	Early arrival of 'dilute' groundwater would not change the number of deposition holes experiencing canister failures. Early deep penetration of such groundwater only affects the start time for the small number of deposition holes with intersecting fractures having sufficient flow rate and aperture to allow erosion.	Early deep penetration of such groundwater affects the start time for the small number of deposition holes with intersecting fractures having sufficient flow rate and aperture to allow erosion. The evolution and arrival of 'dilute' (~<4 mmol/L limit) waters to repository depths may start ~5000 years in the future.
Safety Significance	No safety significant deviation from SR-Site analyses.	No safety significant deviation from SR-Site analyses.	Safety significant deviation from SR-Site analyses not likely. The number of deposition holes in which buffer erosion would occur would not change from early deep circulation of dilute groundwater because other factors (fracture aperture, groundwater velocity) constrain the number of hole capable of significant buffer erosion.	Safety significant deviation from SR-Site analyses not likely. SKB (2011, page 574) states "*…the consequences in terms of canister failures are always bounded by the case where advection is assumed for all canisters throughout the assessment period… [because]…the time taken to erode the buffer to the extent that advection occurs is shorter than that required to cause corrosion failure once the advective conditions are established.*"

Table 6. Impact of penetration of oxygenated groundwater to repository depth.

Topic	Intact Buffer		Eroding Buffer	
	Change in Number of Canister Failed	**Change in General Corrosion Rate**	**Change in Number of Canister Failed**	**Change in General Corrosion Rate**
Additional corrosion by O_2 from deep circulation of oxygenated groundwater during glacial periods	Application of the Extended spatial variability flow model for ice front location III, and assuming application of their deposition-hole rejection criteria, 31 deposition holes are calculated to experience [O_2] levels above 10^{-7}M, and only 6 deposition holes with [O_2] levels above 1mM. The mass-transfer resistance of fractures ($1/Q_1$) also attenuates the number of canisters that would experience significant influx of O_2.	The 'standstill' durations for glacial conditions (ice front III) leading to enhanced deep circulation of dilute, oxygenated groundwater are evaluated for 200 to1000 years; for these assumptions and conservatively disregarding O_2 consumption during sub-surface and buffer transport, the corrosion depths for general corrosion of canisters by O_2 are negligibly small, about $6{\bullet}10^{-6}$ m per year or less.	Similar to "Intact Buffer' case.	Similar to "Intact Buffer' case (although no O_2 consumption by reaction with reducing-minerals in buffer would be possible, although SKB does not take credit for such a process).
Safety Significance	Safety significant deviation from SR-Site analyses not likely. Further sensitivity calculations could be conducted if significantly different DFN models change the number of deposition holes contacted by oxygenated groundwater.	Safety significant deviation from SR-Site analyses not likely. Further sensitivity calculations could be conducted if significantly different DFN models change the number of deposition holes contacted by oxygenated groundwater.	Safety significant deviation from SR-Site analyses not likely. Eroded buffer could only arise for a small number of deposition holes at the end of the next glaciation, greatly reducing any possible safety impacts. Further sensitivity calculations could be conducted if significantly different DFN models change the number of deposition holes contacted by oxygenated groundwater.	Safety significant deviation from SR-Site analyses not likely. Eroded buffer could only arise for a small number of deposition holes at the end of the next glaciation, greatly reducing any possible safety impacts. Further sensitivity calculations could be conducted if significantly different DFN models change the number of deposition holes contacted by oxygenated groundwater.

2014:43

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 315 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se